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SHEAR-VELOCITY STRUCTURE FROM REGIONALIZED

SURFACE-WAVE DISPERSION IN THE BASIN AND RANGE

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ABSTRACT

Lateral variations of shear-velocity structure in the western United States are studied using observations of Rayleigh- and Love-wave phase velocity dispersion. We measured Rayleigh-wave dispersion in the 6-60 sec period range on over 80 paths using both single- and two-station methods. Love-wave dispersion was also measured on about 50 paths. A pure-path regionalization method employing a block-province grid is used to determine lateral variations of dispersion in the Basin and Range and adjacent geologic regions. Structural inversions of the regionalized Rayleigh-wave dispersion curves indicate significant lateral variations in the crust and upper mantle structure of the Basin and Range and transition areas. A pronounced low-velocity zone in the upper mantle is found under the Eureka heat flow province in the central Basin and Range. The lithospheric thickness in this province is 45 km in contrast to the Great Basin model of Priestley and Brune (1978; ~65 km). Regionalization of Love-wave data, together with the Rayleigh wave results, suggest the existence of polarization anisotropy in many areas of the Basin and Range. If verified, anisotropy must be accounted for in phase velocity inversions for the structure of the Basin and Range.

INTRODUCTION

The Basin and Range Province of the western United States has been the focus of a large number of geological and geophysical studies aimed at understanding its formation and mechanisms of extension. Lateral variations in heat flow, P_n velocity, crustal thickness, etc. supply clues about processes in the upper mantle, but more direct observations of the lateral variations in upper mantle structure are needed to determine the driving mechanisms of lithospheric extension. In particular, shear velocity information is extremely valuable since it is a sensitive indicator of the physical state and composition of the crust and upper mantle. For this purpose, measurements of surface-wave dispersion are very useful because shear waves (e.g. S_n) are rarely observed in the Basin and Range. Additionally, joint measurements of Rayleigh- and Love-wave dispersion can provide information about velocity anisotropy in the crust and upper mantle which may reflect the regional tectonic fabric and flow patterns (Tanimoto and Anderson, 1985). In this paper, we present preliminary results showing significant lateral variations of shear velocity structure in the Basin and Range based on many observations of Rayleigh-wave phase velocity dispersion. Furthermore, Love-wave dispersion, together with the Rayleigh-wave results, suggests the existence of polarization anisotropy in the crust and upper mantle for many regions of the Basin and Range.

DATA

We have measured Rayleigh-wave phase velocity dispersion in the 6-60 sec period range for over 80 paths in the western United States using both single-station and two-station methods. Love-wave dispersion was also measured for about 50 paths. The Rayleigh-wave paths are shown in Figure 1 and can be seen to provide dense coverage for areas of the Basin and Range, Colorado Plateau, and southern Columbia Plateau and Snake River Plain.

A vast majority of the measurements were made following the single-station method on earthquakes with known source mechanisms and depths and using stations of the World Wide Standard Seismographic Network (WWSSN). In a few instances, we used digital stations in Nevada and California operated by the Lawrence Livermore National Laboratory (LLNL) and Sandia Laboratory. Two-station dispersion curves were available between WWSSN stations from the study of Biswas and Knopoff (1974) and were also measured between the four Livermore-operated stations (Sheehan, 1984). The estimated standard errors were 1-2% for the single-station velocities and 2-3% for the two-station measurements. The errors are smaller for the single-station measurements because the paths were generally longer than those for the two-station measurements. The total variation of the

Rayleigh-wave velocities on these paths was about 10% at 50 sec and 13% at 10 sec period.

REGIONALIZATION OF PHASE VELOCITIES

The dataset of phase velocity dispersion curves was analyzed for lateral variations using a pure-path regionalization method. This method has been widely applied to long-period observations both in the oceans and the continents and in numerous global studies (see Souriau and Souriau 1983, for a review.). In this study, an attempt was made to remove some subjectivity in the choice of regionalization zones by employing a block-province grid as shown in Figure 1. The idea was to use blocks in areas with dense, criss-crossing paths and tectonic provinces on the perimeter of the study area. This permitted a more objective analysis of the lateral variation of velocity in areas of interest, specifically the Basin and Range and adjacent geologic regions. The block-province regionalization consists of 20 zones, 16 of which are square blocks 300 km on a side and four are tectonic provinces with boundaries defined by the Cascades and northern Columbia Plateau (zone 1) , northern Rocky Mountains (zone 2) , southern Basin and Range (zone 19) , and the Great Plains (zone 20; Figure 1). The size of the blocks and hence number was chosen by taking into consideration the number of paths and wavelengths of the surface waves. Following the standard methodology, the total observed phase slowness on any selected path at a given period is a linear combination of the phase slownesses of each zone weighted by the fraction of the path in each zone. Inversion for the phase slownesses of each zone was carried out by simple least squares involving, in the case of Rayleigh waves, some 80 equations and 20 unknowns. Inversions were carried out independently at each period sample on the dispersion curve.

Both the residuals and the slownesses themselves were checked carefully to evaluate the inversion performance. The residuals showed an RMS value of about ±1.5%, which is satisfactory considering the estimated error for individual dispersion curves. An independent check on the slownesses was made against published surface-wave studies involving short paths in the western United States (e.g. Greenfelder and Kovach, 1982, for the Snake River Plain; Priestley and Brune, 1982, for northern Great Basin; and Keller *et al.* 1979, for the Colorado Plateau) and the comparisons were satisfactory over the entire period range. The velocities associated with blocks having good sampling and a crossfire of paths are the most reliable (Figure 1).

The inversion results showing lateral variations of Rayleigh-wave phase velocity in four period ranges are presented in Figure 2 where percent deviations from a reference dispersion curve for the Great Basin (Priestley and Brune, 1978) are shown. The period range from 25 - 50 seconds generally samples the lower crust and upper mantle and the range from 10 - 24 seconds mainly samples the mid to upper crust. The results in Figure 2 indicate significant lateral velocity variation in the Great Basin although the spatial-average velocity agrees quite well with the dispersion obtained by Priestley and Brune. Low velocities are found in areas of the Eureka heat flow low (block 12) and in parts of southeastern Oregon (block 3) . High velocities are found in transition areas such as the Intermountain Seismic Belt (blocks 8 and 13) and the Mohave Desert (block 15) , and in the Battle Mountain heat flow area (blocks 4,6 and 7) . Interestingly, as will be further discussed below, the pattern of velocity variations obtained for Love waves (not shown) is in stark contrast to the Rayleigh-wave results. For example, Love-wave velocites are generally higher than the Great Basin velocities in block 12 and slower in block 6, just the opposite of the Rayleigh-wave variations.

INVERSION OF REGIONALIZED PHASE VELOCITIES

The regionalized phase velocity curves for the blocks extending from the northwestern edge of the Basin and Range to the southeast in the Colorado Plateau (blocks 6,7,12,13,17; Figure 1) were inverted for shear velocity structure in an attempt to develop a structural cross-section. The Rayleigh-wave dispersion for each block was inverted for shear velocity structure using a maximum-likelihood technique in which the data errors are used to weight the inversion (Wiggins, 1972). A range of initial models was used for each inversion that differed mainly in the crustal thickness. Initial crustal velocities consisted of a 3.5 km/s upper layer and a 3.8 km/s lower layer similar to that of Priestley and Brune (1978). Layer thicknesses were set at 5 km for the crust, 10 km for the uppermost mantle, and 20 km for the lower portions of the model. Final models were selected on the basis of being physically reasonable and on constraints obtained from previous geophysical studies. For each block, some structural information based on results from refraction surveys and previous surface wave studies is available. As an example, for blocks 7 and 12, fairly detailed crust and upper-mantle velocities are discussed in Hill and Pakiser (1966) and Stauber and Boore (1978) among others. These studies allow us to place constraints on crustal structure which makes our upper mantle velocities better determined. Using these constraints, and from sensitivity studies, we feel that we can estimate the average crustal thickness for each block to within ± 5 km. However, given the relatively large size of each block, it is expected that the crustal thickness varies by this much particularly where a tectonic boundary is encountered.

Resolution calculations indicate that, for the period range used, layers between approximately 10 - 30 km were resolved the best. Standard errors on the layer-velocity estimates were generally about $\pm$ 0.2 km/s and final RMS fits were typically about 0.03 - 0.05 km/s.

The preferred velocity models are shown in Figure 3 which basically represents a W-NW to S-SE profile for the six blocks extending across the Basin and Range into the Colorado Plateau. Because of limitations in model resolution, small features such as single-layer crustal low-velocity zones are probably not significant.

DISCUSSION

A principal feature of the profile in Figure 3 is the presence of a well-developed, upper mantle low velocity zone in the central Basin and Range (block 12). The lid thicknesses in Figure 3 are quite thin (~10 - 30 km) relative to that of the Great Basin model (Priestley and Brune, 1978; ~30 km). The top of the upper mantle low velocity zone may actually be a negative velocity gradient rather than an abrupt velocity discontinuity. However, resolution calculations indicate that we cannot distinguish between the two possibilities without additional constraints such as S_n velocities.

As discussed above, the crustal thickness was primarily selected to match constraints from regional refraction results and appears to be thick (~35 km) in the central part of the Basin and Range and thin (~25 km) on the outer edges. The central part of the Basin and Range also appears to be characterized by slightly higher velocities in the lower crust compared to the northwest block (block 6) which has uniformly low velocities throughout the thin crust.

The upper-mantle lid appears to be thicker in the northwestern Basin and Range and its character on the Wasatch Front (block 13) becomes unclear. The location of the Moho in block 13 is either at about 20 km depth or at 45 km depth. This feature is very similar to the "double Moho" described by Pechman *et al.* (1984) based on earthquake and quarry blast travel times in the same region. Surprisingly, the S-velocities in this transitional block are very similar to those located to the east in the stable Colorado Plateau block. However, the S-velocities of 4.0 km/s at depths of 20 to 45 km correspond to P-velocities of about 7.4 km/s (Keller *et al.*, 1975), while those on the Colorado Plateau correspond to P-velocities of about 6.8 km/s. Thus, these depths in the transitional block are characterized by very high Poisson's ratios (0.29 as opposed to 0.24 in the Colorado Plateau).

The dramatic increase in Poisson's ratio could be due to the effect of partial melt or of some high temperature relaxation mechanism acting in this transitional region. Theoretical calculations for partially melted mantle material contained in thin, interconnected cracks suggest that the observed low velocities (e.g. 4.0 vs 4.5 km/s) are not unreasonable for plausible crack densities (O'Connell and Budiansky, 1977). However, it is not clear if the high Poisson's ratio layer between approximately 20 45 km depth is composed of mantle-derived crustal material or of ultramafic mantle material whose velocities are reduced by high temperature effects. Furlong and Fountain (1985) point out that in regions undergoing crustal underplating, significant amounts (>10 km) of mantle-derived crustal material can be emplaced at the base of the crust. Consideration of the resultant seismic velocities suggests that, for many cases, the added material may have velocities intermediate between those typical for crust and mantle petrologies.

As discussed above, we also carried out a regionalization on Love-wave velocities using the same block configuration shown in Figure 1. Areas in the northwest (block 6) and in the eastern transition (block 13) have low Love-wave velocities, and structural inversions of the Love-wave dispersion suggest that the SH layer velocities are low compared to the SV velocities obtained from the Rayleigh wave inversions. In contrast, the central Basin and Range (block 12) has relatively high Love-wave phase velocities, and SH layer velocities are greater than SV velocities.

While these results are suggestive of polarization anisotropy, several factors need to be considered to verify that it is indeed real. Interference of higher-mode Love waves with the fundamental mode could introduce errors in the phase velocity measurements, particularly in the period range of 30 - 40 sec (Patton and Taylor, 1984). Additionally, lateral velocity heterogeneity not accounted for by the regionalization grid may cause systematic errors in the inverted slownesses at shorter periods. To further test the regionalization results, we plan to make additional dispersion measurements, particularly over short paths in areas showing strong anisotropy. We also plan to improve the stability of the pure-path regionalization by grid shifting and averaging.

If there is significant polarization anisotropy, it must be considered in our structural inversions. As discussed by Anderson and Dziewonski (1982), isotropic inversion of Rayleigh-wave phase velocities in a region characterized by strong polarization anisotropy can produce models with pronounced low-velocity zones, while anisotropic inversion of the same data yield models with more nearly constant velocities. Furthermore, the addition of S_n velocities would provide more details of the upper mantle structure. Although S_n is rarely recorded in the Basin and Range, we have occasionally observed it on broadband seismograms of the LLNL network and plan to measure apparent velocities to constrain future inversions. Future studies which may include the effects of lateral variations of velocity anisotropy will provide more details of the three-dimensional structure of the Basin and Range and will lead to a better understanding of the causes of lithospheric extension.

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REFERENCES

Anderson, D.L. and A.M. Dziewonski, Upper mantle anisotropy: evidence from free oscillations, *Geophys. J. R. astr. Soc.*, 69, 383-404, 1982.

Biswas, N.N. and L. Knopoff, The structure of the upper mantle under the United States from the dispersion of Rayleigh waves, *Geophys. J R. astr. Soc.*, 36, 515-539, 1974.

Furlong, K.P. and D.M. Fountain, Continental crustal underplating: model and implications, submitted to *J. Geophys. Res.*, 1985.

Greensfelder, R.W. and R.L. Kovach, Shear wave velocities and crustal structure of the eastern Snake River Plain, Idaho, *J. Geophys. Res.*, 87, 2643-2653, 1982.

Hill, D.P. and L.C. Pakiser, Crustal structure between the Nevada Test Site and Boise, Idaho, from seismic refraction measurements, in The Earth beneath the Continents, Am. Geophys. Un., Geophys. Mon., 10, 391-419, 1966.

Keller, G.R., R.B. Smith, and L.W. Braile, Crustal structure along the Great Basin-Colorado Plateau transition from seismic refraction studies, *J. Geophys. Res.*, 80, 1093-1098, 1975.

Keller, G.R., L.W. Braile, and P. Morgan, Crustal structure, geophysical models and contemporary tectonism of the Colorado Plateau, Tectonophys., 61, 131-147, 1979.

O'Connell, R.J. and B. Budiansky, Viscoelastic properties of fluid-saturated cracked solids, *J. Geophys. Res.*, 82, 5719-5736, 1977.

Patton, H.J. and S.R. Taylor, Q structure of the Basin and Range from surface waves, *J. Geophys. Res.*, 89, 6929-6940, 1984.

Pechmann, J.C., W.D. Richins, and R.B. Smith, Evidence for a "Double Moho" beneath the Wasatch Front, Utah, Trans. Am. Geophys. Un., 65, 988, 1984.

Priestley, K. and J. Brune, Surface waves and the structure of the Great Basin of Nevada and western Utah, J. Geophys. Res., 83, 2265-2272. 1978.

Priestley, K.F. and J.N. Brune, Shear wave structure of the southern volcanic plateau of Oregon and Idaho and the northern Great Basin of Nevada from surface wave dispersion, *J. Geophys. Res.*, 87, 2671 - 2675, 1982.

Sheehan, A.F., Interstation phase velocities in the Basin and Range, B.S. Honor Thesis, Univ. of Kansas, 30pp, 1984.

Souriau A. and M. Souriau, Test of tectonic models by great circle Rayleigh waves, *Geophys. J. R. astr. Soc.*, 73, 533 - 551, 1983.

Stauber, D.A. and D.M. Boore, Crustal thickness in northern Nevada from seismic refraction profiles, *Bull. Seism. Soc. Am.*, 68, 1049-1058, 1978.

Tanimoto, T. and D.L. Anderson, Lateral heterogeneity and azimuthal anisotropy of the upper mantle: Love and Rayleigh waves 100 - 250 s. *J. Geophys. Res.*, 90, 1842-1858, 1985.

Wiggins, R.A., The generalized linear inverse problem: Implications of surface waves and free oscillations for earth structure, Rev. Gephys. and Space Phys., 10, 251-285, 1972.

FIGURE CAPTIONS

Figure 1. Map of the western United States showing (a) seismic stations, tectonic provinces, and the block-province grid employed by the regionalization method and (b) Rayleigh-wave paths.

Figure 2. Results of the phase velocity regionalization method applied to the Rayleigh-wave data. The results are given in four period ranges as percent deviations from the Great Basin dispersion curve of Priestley and Brune (1978). Shading denotes areas with velocities greater than the Great Basin curve, and stippling denotes areas with slower velocities. Unmarked areas have velocities not significantly different from the Great Basin curve.

Figure 3. Final shear-velocity models from isotropic inversion of regionalized Rayleigh-wave phase velocities for six blocks across the Basin and Range (see Figure 1).

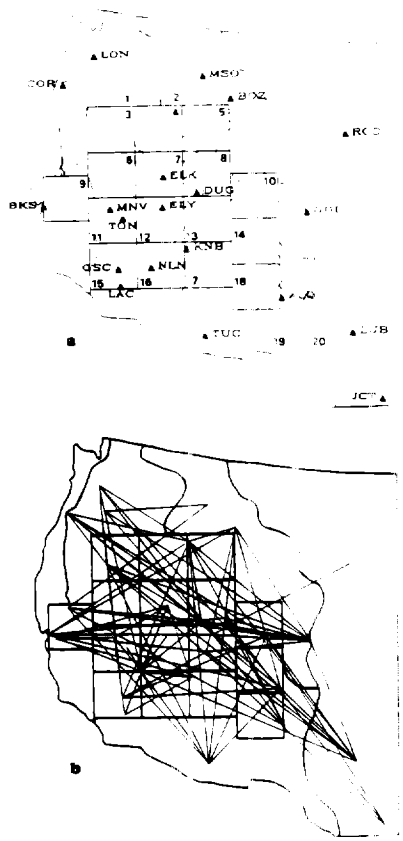

Fig. 1

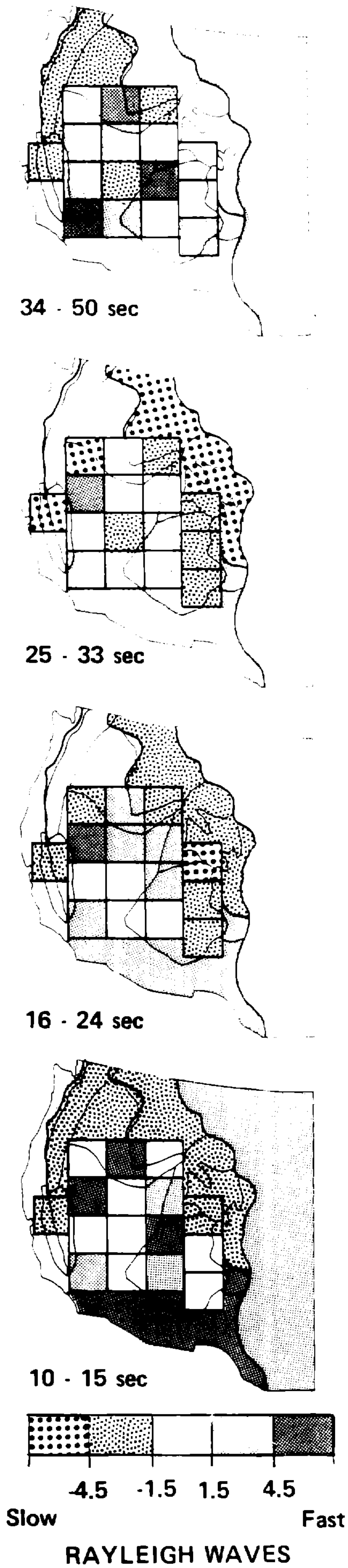
34 - 50 sec
25 - 33 sec
16 - 24 sec
10 - 15 sec
-4.5 -1.5 1.5 4.5
Slow
Fast
RAYLEIGH WAVES

Fig. 2

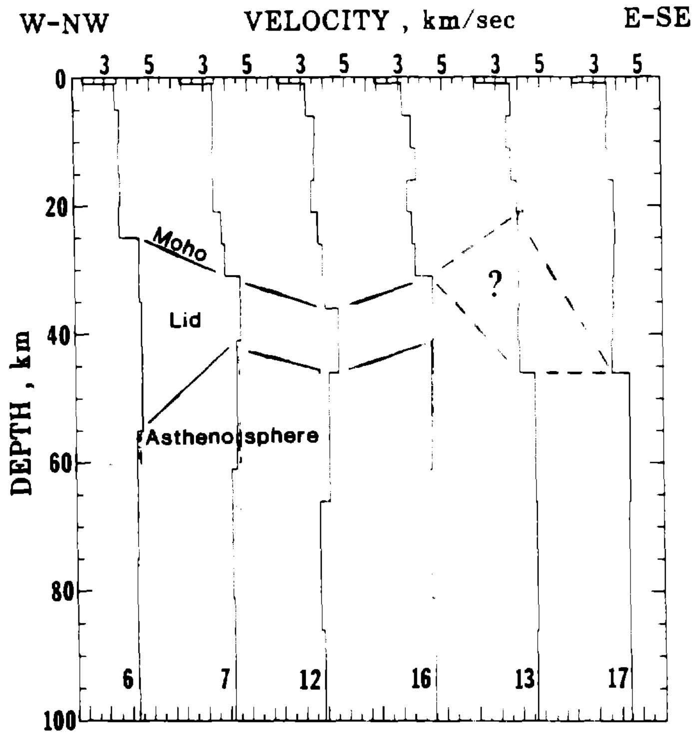
W-NW
VELOCITY , km/sec
E-SE
3
5
3
5
3
5
3
5
3
5
3
5
0
20
40
60
80
100
DEPTH , km
Moho
Lid
?
Astheno sphere
6
7
12
16
13
17

Fig. 3